

Design of biomass and natural gas based IGFC using multi-objective optimization



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ABSTRACT

Integrated Gasification Combined Cycle (IGCC) and Integrated Gasification Fuel cell Cycle (IGFC) uses Syngas in fuel cells and gas turbines to produce power. Several designs have been studied and it is common to analyze different designs (one at a time) to understand which design is more efficient. In this work we propose a superstructure that has both fuel cell topping and fuel cell bottoming cycles and use multi-objective optimization (MOO) to obtain optimal designs. The capacity of the fuel cells and the gas turbines in the superstructure is a decision variable and this gives an opportunity to size the system more efficiently. Here, we use two objectives, one is the energy generated by fuel cells while the other is the energy generated by the gas turbines in MOO and the analysis of the Pareto front gives us many networks. We identified different networks that produce about the same amount of energy when biomass is the fuel. However, when natural gas is used as fuel, the fuel cell only network produces more energy than other networks. Further, it was observed that it is only possible to produce more energy in IGFCs when the combustion and gasification units are maintained at Gibbs equilibrium.

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1. Introduction

Human population is constantly increasing. This combined with rapid economic growth and development around the world is leading to an ever-increasing demand for fuels. In view of this, alternative resources of energy are gaining importance. According to the International Energy Agency (IEA) [1], energy from biomass would constitute 23% of the total world energy use by 2050. The use of biomass would reach 3600 Mtoe/yr (Million Tons of Oil Equivalent per year) of which 700 Mtoe/yr would be used to produce liquid fuels for the transportation sector, 700 Mtoe/yr for the generation of power and 2200 Mtoe/yr for the production of bio-chemicals, district heating, cooking, and industrial steam. This translates to 15 Billion t/yr of biomass being transported to centralized locations. In order to minimize the energy used in the transportation of large amounts of biomass and also to minimize the transmission losses in the power sector, it may be worthwhile to produce power at decentralized locations that serve smaller communities. As a result, distributed energy systems (DES) are gaining importance [2].

The global energy demand was about 400 Quadrillion BTU in the year 2000 and is expected to increase to 1200 Quadrillion BTU by the year 2040 [3]. Energy savings through improved efficiencies have the potential to reduce this demand to 700 Quadrillion BTU. Furthermore, in view of the increasing awareness on climate change, the US Department of Energy (DOE) has set a target of 60% efficiency (higher heating value) for next generation coal fired power plants and it was observed that current designs have not achieved this goal [4]. Thus, further optimization to improve the design of IGCC/IGFC systems is necessary. This together with the advantages of operating a DES motivates us to focus on the optimal design of an IGFC system.

The process of production of syngas from biomass/coal for use in the generation of power is called an IGCC (integrated gasification combined cycle) and when the syngas is used in a fuel cell it is called as an IGFC (integrated gasification fuel cell cycle). The IGCC/IGFC systems also consist of gas cleaning systems, steam turbines, gas turbines and heat exchangers. Briefly, the biomass i.e., wood chips or plant stalks are processed and fed to the gasifier to produce syngas at a high temperature. The produced syngas is then cleaned to remove any particulate matter and toxic substances that may foul the fuel cell. The syngas may be passed through a water–gas shift reactor to increase the hydrogen content. The high

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temperature gas makes it an ideal fuel for high temperature fuel cells and improves the efficiency of the integrated system. The efficient design of a high temperature gas clean up system is critical for the practical implementation of the IGFC system. Alternatively, the syngas may be cooled and the gas clean up may be done at a lower temperature using more efficient gas clean up systems. If this is done, the cleaned syngas must be reheated, thus compromising the efficiency [5].

2. Literature review

In view of the rather limited availability of comprehensive review and models of all the three major components of IGFCs in one research paper, we first present a review of biomass gasification, fuel cells and gas turbines.

2.1. Biomass gasification

Biomass and coal gasification have been studied extensively over the past few decades. Gasification is a process wherein the biomass undergoes devolatilization at lower temperatures (about 300 °C–400 °C) followed by tar cracking and gas phase reactions at higher temperatures (400–800 °C). In some instances the temperature of coal gasification can reach 1400 °C [6]. Some of the earliest gasification studies include those of Ergun [7], where coke gasification was studied extensively and the composition of syngas at various temperatures was obtained. Several studies on the combustion rate of carbon [8], the kinetics of char combustion in a fluidized bed [9], mathematical models for thermal decomposition of coal [10–14] and combustion and gasification kinetics of pyrolysis chars from waste and biomass [15] are presented in literature. All these studies focused on the devolatilization of biomass and change in weight of the initial biomass with temperature.

At above 800 °C, combustion is dominant if oxygen is present. However, in a gasification unit, drying, pyrolysis gasification and combustion all occur simultaneously [16]. Gasification is an endothermic process and the energy released from the combustion process is used to supply the energy required for gasification. This process leads to the evolution of tars, char and gases such as CO, CO₂, H₂O, H₂, CH₄ and higher hydrocarbons.

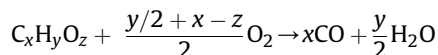
A comprehensive review on the process of biomass gasification in a fluidized bed gasifier was presented by Gomez-Barea and Leckner [17]. The overview can be divided into two parts. One, the process of biomass devolatilization, change in particle size of the biomass and the process of tar cracking and two, the gas phase reactions. They validated the models for the first part. In the second part, they compiled data from several sources and have given the values of the pre-exponential factors and the activation energy in the Arrhenius rate equation. They have shown in their compilation that these values vary widely, sometimes by a factor of 10⁵. Vitasari and co-workers worked on exergy analysis of biomass to synthetic natural gas production via Syngas. They have observed that the largest losses occur in the Syngas Gasifier [18] and this is possibly due to the presence to steam for water–gas shift reaction.

Several reactions occur in a biomass gasification unit. Biomass devolatilization occurs as:

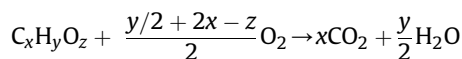


Tar is assumed to have a general formula CH_xO_y where $x = 8/6$ and $y = 1/6$ and Char is assumed to be C_s although in reality it is only about 95% carbon.

Partial combustion and complete combustion of Tar occurs as:



and



In addition to the above reactions, various other reactions occur in biomass gasification, however these are not presented here.

Perez-Fortes et al. [19] developed a gasifier model that is based on a series of experimental correlations and used the model in the simulation of an IGCC. Development of such correlations requires extensive availability of data. Schuster et al. [20] simulated the process of biomass gasification assuming that the products of the gasification process are in thermodynamic equilibrium. The same research group developed a model for biomass char combustion in a fluidized bed gasification unit [21]; however, this model was not validated with experimental results. In a later study [22], they presented a model for biomass gasification considering thermodynamic equilibrium, hydrodynamics in the fluidized bed, reaction kinetics and elemental balance and showed that their model fitted experimental results very well [20,23]. One of the important reactions in the process of biomass gasification is the water–gas shift reaction, where carbon monoxide is oxidized to carbon dioxide thereby reducing the water molecule to hydrogen and effectively increasing the concentration of hydrogen in the products. A study on the water–gas shift reaction kinetics and an equation for the equilibrium constant of the reaction was presented by Choi and Stenger [24]. This reaction is important for fuel cells such as the PEMFCs that do not tolerate carbon monoxide. Others [25] have studied the kinetics of the reaction of char with carbon dioxide and steam. In addition to these studies, several researchers have investigated the reaction kinetics of coal chars and other biomass using a thermo-gravimetric analyzer [26–30].

Neural networks were used by some researchers for simulating biomass gasification [31]. However, no information on the amount of data used in developing the neural network model was presented. Free energy minimization and Gibbs equilibrium are widely used by various researchers to study the product composition in a biomass reforming/gasification unit and a free energy minimization approach for carbon dioxide reforming of methane [32]. Both experimental and modelling analysis of a gasification/pyrolysis reactor was performed by Baggio et al. [33]. They used significant quantities of saw dust (up to 375 g) in a batch reactor. However, their model and comparison of the experimental and modelling results are limited only to changes in weight of biomass with temperature. Thus, their experimental results are limited and insufficient to convincingly validate the model.

2.2. Fuel cells and gas turbines

Researchers have developed different types of fuel cells and they are classified based on the electrolyte employed. Solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) have a wide range of applications and can use CO as fuel. Hence they are suited for integration with biomass gasification units.

The National Fuel Cell Research Center (USA) has done considerable work in the control of (SOFC) – micro-gas turbine (MGT) hybrid system for the generation of power. In their work, they consider that the fuel of known composition is readily available for use in the hybrid system. They have presented cycles such as fuel cell (FC) topping, fuel cell bottoming, direct and indirect cycles. A detailed two dimensional planar SOFC system integrated with a gasification unit was studied and it was shown that the detailed

model allows prediction of temperature changes at various points across the SOFC [34]. This allows for the safe operation of the hybrid system. The detailed model predicts that a high airflow rate is required to keep the SOFC within safe temperature limits, thus reducing the efficiency. The load following capability, control system design, and power/temperature control of a fuel cell combined cycle power plant having fixed and variable speed gas turbines under varying fuel feed has been investigated by various researchers [35–38]. However, these works also assume that the fuel gas composition is fixed and known; furthermore, the rate at which the flow rate changes with time is also known.

Similarly, models for SOFC integrated with MGT have been studied and the simulation results have been compared with experimental data [39,40]. These works also assume that syngas at known composition is readily available. Models for tubular SOFC which have an internal methane reformer along with models for compressor and turbine maps were developed and studies on full and part-load operation of the SOFC have been conducted by Chan et al. [41–43]. Others have also studied the design and part-load performance of a tubular SOFC having a methane reformer [44]. Murshed et al. [45] presented a control relevant model of a planar SOFC consisting of a methane reformer and a capacitor and observed that the system with the capacitor has better transient properties. They also considered the estimation and control of the solid oxide fuel cell system and using Kalman filter and model predictive control respectively [46]. Bang-Møller et al. [47] performed an exergy analysis of a biomass gasification–SOFC–MGT system. They used the Gibbs equilibrium for the gasification process and a simple model for the SOFC. They considered a system where the SOFC–MGT system and the gasification system are decoupled and suggested improvements such as using hot gas for preheating, using exhaust gas for drying biomass and optimizing the SOFC stack temperature to improve the efficiency of the combined system. In a newer study, Bang-Møller et al. [48] demonstrated biomass gasification coupled with SOFC based on data from a 0.6 MWth gasifier. The dynamic behavior of a hybrid power generation system consisting of a wind turbine, microturbine, solar array and a battery storage system was studied by Kalantar and Mousavi [49], while other researchers have proposed models for real time simulation of medium-size gas turbines [50].

2.3. Integrated gasification fuel cell cycle

The products of the gasification system are at a high temperature and the SOFC also operates at a high temperature. With efficient high temperature gas cleaning technologies, these two systems can be combined to form an integrated system where the net efficiency is possibly higher than a system that employs traditional steam turbines or if the gas were to be cooled and shipped to the location where the SOFC is located. Due to this synergy, the study of IGFC systems is gaining popularity.

An SOFC system that is coupled to a biomass gasification unit was studied using Aspen Plus (RYIELD) at steady state [51–53]. Biomass gasification in the considered system occurs through an aliothermal process wherein the heat exchange between the combustion unit and the gasification unit occurs through the use of sodium heat pipes. Others researchers have also used Aspen Plus for simulating the biomass gasification process; however, they used the RIGIBBS reactor instead and simulated a gasification–SOFC process [54]. Biomass gasification process was modelled as a reactor under Gibbs equilibrium and a study on high and low temperature fuel cells – both SOFC and PEMFC either individually or in parallel/series was performed by Heidebrecht et al. [55]. They observed that a system with SOFC and PEMFC in series offers higher

efficiency than that in parallel, which in turn offers higher efficiency than a lone SOFC.

An evolutionary algorithm for MOO (multi-objective optimization) and optimal design of a combined cycle power plant was used by Ahmadi et al. [56]. Some of the key decision variables considered in their work are turbine inlet temperature, compressor pressure ratio, isentropic efficiency of the compressor and the turbine. They also considered maximizing the energy efficiency, minimizing the cost and carbon dioxide emissions as their objectives. More recently, they have used MOO to design a novel multi-generation system that includes biomass combustor, adsorption chiller for cooling, and proton-exchange membrane electrolyser for hydrogen production [57]. Others [58] have studied the biomass gasification fuel cell and biomass gasification combined cycle systems using Aspen Plus and compared the energy efficiency and emissions performance of the two systems. They also considered the biomass gasification unit as operating under Gibbs equilibrium. A techno-economic performance of recuperated and non-recuperated variable speed microturbines in a combined heat and power generation system when the turbine inlet temperatures and shaft speeds are varied has also been presented [59]. Key observations from these studies are that these systems have a high fuel utilization of about 80% and a normal load tracking capability of 1 kW/s for a 200 kW system.

2.4. This work

As seen earlier, biomass gasification has been widely studied under different conditions and a wide range of models and model parameters are available. Out of the several models, the model based on Gibbs free energy minimization is used here because it is founded on the laws of thermodynamics and the reliability of the model is very high. Since this approach assumes that the total Gibbs free energy of the products is at its minimum, we would essentially solve an optimization problem that satisfies the constraints of mass and energy balance.

A lumped parameter model presented by Murshed et al. [45] is used to represent fuel cells. The mass balance in fuel cell model is fairly straightforward because only CO and H₂ oxidation are considered. However, an optimization problem to satisfy energy balance is still required.

In this work, we present models for biomass gasification, fuel cells and gas turbine. We also outline a solution strategy to calculate the composition of the products and the energy generated from the system. Further, we propose that the IGFC system can be designed by optimizing a design superstructure using multi-objective optimization. In literature, it is common to propose a design and optimize the same for the operating conditions. The process is repeated when the sizes of the equipment changes. Considering that there are a vast number of combinations available for the size of the fuel cell stack and gas turbine, we propose a superstructure and optimize it using MOO. This has not been undertaken before possibly because computational power has become cheaply available only recently. The schematic of the superstructure is shown in Fig. 1. By optimizing a design superstructure, we aim to obtain a completely new design that was not envisaged before. Further, we seek to highlight that superstructure design optimisation can be achieved in reasonable computational time. In addition, existing literature focused on the combustion/gasification processes at Gibbs equilibrium while we analyze scenarios where the combustion/gasification units do not achieve Gibbs equilibrium so as to better simulate reality.

Alternative methodologies: before we proceed, it is important to mention about alternative methodologies. First, the CO and CO₂ emissions per MW are directly related to the efficiency of the

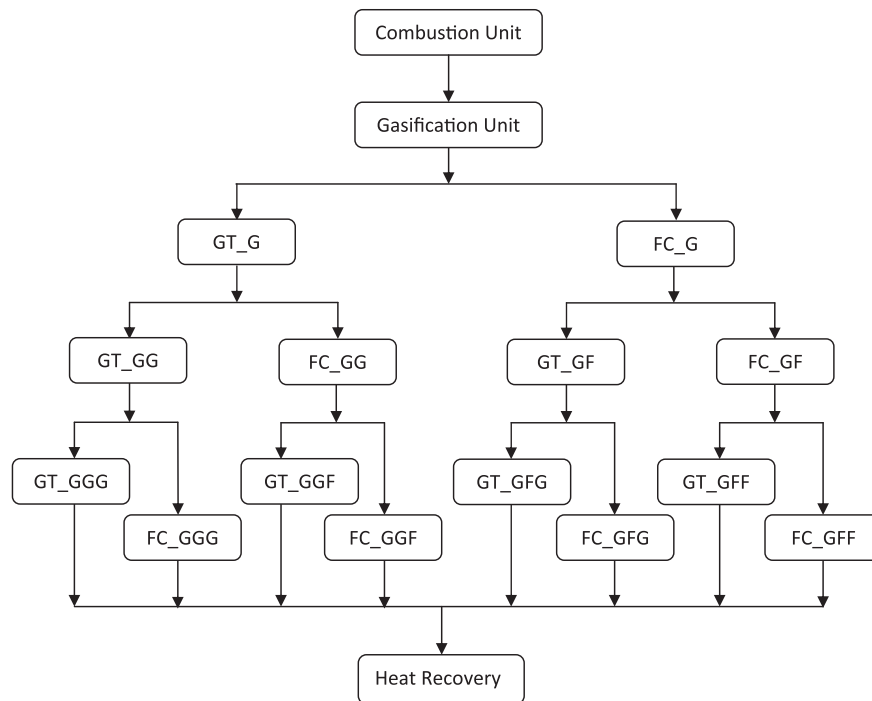


Fig. 1. Superstructure of IGFC considered in this study. GT, gas turbine; FC, fuel cell; _G, downstream to gasification unit; _GF, downstream to gasification unit and fuel cell stack; _GFF, downstream to gasification unit and two fuel cell stacks; _GG, downstream to gasification unit and gas turbine; _GGG, downstream to gasification unit and two gas turbines.

system (and the type of fuel). Hence it would suffice if we aim for maximum efficiency without directly accounting for CO₂ emissions. This is because a more efficient system would release less CO₂ per MW. However, waste energy from the power plant can be used in CO₂ capture and this was studied elsewhere [60] and it is beyond the scope of this work to consider CO₂ capture in a superstructure. In view of this, we do not consider CO₂ emissions, but only strive for a system that has maximum efficiency. Further, NO_x and SO_x emissions are dependent on the type of fuel and the operating conditions and separate equipment are required to treat product gases before they can be released into the atmosphere. In view of this, these are not considered in the superstructure.

Second, a genetic algorithm with a single objective cannot generate multiple networks unless a diversity measure is incorporated in the algorithm [61]. In view of this, we have tried multi-modal optimization with a single objective (total energy generated by the system); however the results were not promising (results are not presented here). The efficiency of the multi-modal optimisation algorithm depends on the number of variables that are considered in the diversity measure. There are only two variables (energy generated by fuel cells and gas turbine) that are related to diversity and these are not sufficient to derive an effective diversity measure. Hence, we used multi-objective optimization to generate multiple networks simultaneously. The two objectives considered in MOO are the energy generated by fuel cells and the energy generated by the gas turbines. It is obvious that if one objective is maximized, the other would be reduced for a given amount of fuel.

Third, economics (CapEx) are fairly complex (in part because they are market dependent) and using complex economic models in a superstructure such as this would make the problem intractable; on the contrary, simple economic models (based on two-third rule and factors/indices) do not give us the necessary insight that is required in this fairly complex superstructure. Further, another objective would be required to consider economic objectives. In view of this, techno-economic analysis (CapEx) is best

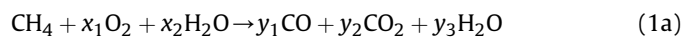
performed on a given design, one at a time rather than on a superstructure. Hence we do not consider economics in our objective. Further, operational costs due to amount of fuel consumed and the penalty due to CO pollution need not be considered when efficiency is being maximized because fuel use per kWh and CO production per kWh would be at a minimum.

Next, we demonstrate through an example as to why it would suffice to use efficiency in design of power plants.

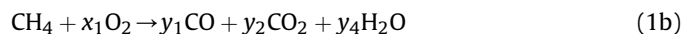
2.5. Example

Three objectives are sometimes used for optimal design of power plants. These three objectives are: energy efficiency, CO₂ minimization, and minimization of CO penalty costs. However, we demonstrate here that only one objective would suffice when power plants are designed. Consider natural gas as a fuel of choice.

The general equation for the overall power plant can be written as:



It must be mentioned here that all coefficients are positive. Further, $y_3 > x_2$ (always) and hence the equation can be rewritten as:



Again, the coefficients are all positive. The efficiency of a power plant is related to the extent of the net chemical reaction; it also depends on the physical equipment that are present and their operating conditions. First, consider the extent of chemical reaction. For the purpose of this example, we consider three scenarios: (1) complete combustion where all the carbon is converted to CO₂ (and no CO is produced), (2) extreme partial combustion where all the carbon is converted to CO (and no CO₂ is produced) and (3)

partial combustion where half of the carbon is converted to CO and the other half to CO₂. The values of the coefficients and the change in enthalpy of each of the scenarios are presented in Table 1a.

It is obvious that the enthalpy change for this process will always lie between −519 kJ/mol (minimum) and −802 kJ/mol (maximum). When the enthalpy change is maximum, the efficiency of the process is the highest and the CO production is zero. That is, the pollution penalty costs associated with CO emissions are zero. Further, the CO₂ emissions are at its maximum. In other words, if we were to strive for maximization of the efficiency, then the costs due to penalty on CO are automatically at its minimum and the CO₂ emissions are at its maximum. Further, the per unit cost of production of electricity would be at its minimum when efficiency is at the maximum because the minimum possible fuel is consumed. On the other hand, when CO₂ needs to be minimized, CO production would be at its maximum (and hence the CO penalty costs would be at the maximum) and the efficiency would be at its minimum. Further, the per unit cost of production of electricity would be at its maximum when efficiency is at the minimum because the maximum possible fuel is consumed.

In the above example, the relationship between the coefficients is linear and hence the analysis was simple. However, complexities arise when the temperature changes because the specific heat of the gases changes non-linearly with temperature. It must be mentioned here that the change in specific heat of gases are always convex with respect to temperature (equations for specific heat are presented later in this article). That is, if we include temperature as a variable in the above equations, it would lead to a convex non-linear program. Hence the analysis that is based on the simple example above will still hold at any temperature. Further, this analysis will hold for any other type of fuel such as coal or biomass because the only difference would be the presence of additional oxygen on the left hand side.

Next, consider the design of the physical plant and the operating conditions. It is important for the designer to minimize losses due to design (that are unrelated to extent of chemical reaction) and also minimize losses due to partial chemical reaction. Although, these look like two different objectives, in reality both of them can be optimized if we consider maximization of efficiency. However, the designer risks getting sub-optimal solutions if the single objective optimization algorithm is not powerful/cannot reach global optimum especially because the design equations are non-convex. In view of this, a secondary objective such as the economic objective that includes a penalty for CO pollution would help maintain diversity in the population and eliminates the problem of the algorithm converging at local optima. In other words, when a powerful algorithm is available, either the efficiency or the economic objective as a single objective would help the designer reach the same objective. It must be noted here that CO₂ minimization cannot be used as a single objective optimization because that

would give us a solution where no fuel is used and thus no energy is produced.

We have in the past demonstrated an algorithm that works well for problems of over 400 variables [61]. In view of the availability of a good algorithm, we only consider maximization of efficiency in our work and do not consider CO₂ minimization and operational costs. It must be reemphasized here that the purpose of MOO in this work is not to overcome the problem of converging at local optima, but to maintain diversity in the population so that multiple networks can be identified at the same time.

3. Mathematical models and solution strategy

3.1. Biomass combustion and gasification

In this section, the mathematical model for biomass gasification using the concept of Gibbs free energy minimization is presented. Gibbs free energy is a function of enthalpy and entropy – the molar enthalpy of formation and the molar entropy at a given temperature is a function of the specific heat at constant pressure. The equations for specific heat at constant pressure for steam, hydrogen, oxygen, carbon monoxide and carbon dioxide are taken from Larminie and Dicks [62].

The change in Gibbs free energy for a given chemical reaction is given by Eq. (1):

$$\Delta \bar{g}_f = \Delta \bar{h}_f - T \Delta \bar{s} \quad (1c)$$

$$\bar{h}_T = \bar{h}_{298.15} + \int_{298.15}^T \bar{c}_p dT \quad (1d)$$

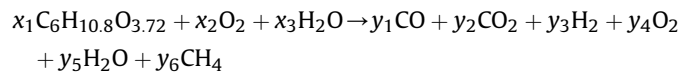
$$\bar{s}_T = \bar{s}_{298.15} + \int_{298.15}^T \frac{\bar{c}_p}{T} dT \quad (1e)$$

Consider for example the reaction $H_2 + 1/2O_2 \rightarrow H_2O$. Here,

$$\Delta \bar{h}_f = (\bar{h}_f)_{H_2O} - (\bar{h}_f)_{H_2} - \frac{1}{2} (\bar{h}_f)_{O_2} \quad (1f)$$

$$\Delta \bar{s}_f = (\bar{s}_f)_{H_2O} - (\bar{s}_f)_{H_2} - \frac{1}{2} (\bar{s}_f)_{O_2} \quad (1g)$$

The equations for specific at constant pressure for various gases are given in Table 1b. The enthalpy and entropy of the various gases at 298.15 K are given in Table 2. For the purpose of this work, a general equation for the mass balance of biomass gasification/combustion process is considered. It is further assumed that only CO, CO₂, H₂, H₂O, O₂ and CH₄ are produced and the amount of tar and char is negligible. Hence, combustion/gasification can be written as:



The general molecular formula for the biomass is assumed to be similar to the composition of empty palm fruit bunches [62]. This is chosen because it is one of the widely available biomass resources in South East Asia. The amount of C, H and O are similar to that reported for wood [47].

The equations for mass balance in the combustion and gasification unit can be written as:

Table 1a

The coefficients for the process of natural gas combustion/gasification along with enthalpy change under various scenarios.

	CH ₄	O ₂	CO	CO ₂	H ₂ O		
Enthalpy (J/mol)	−74,870	0	−110,529	−393,522	−241,827		
		x_1	y_1	y_2	y_4	ΔH (J/mol)	
Complete combustion		1	2	0	1	2	−802,306
Partial combustion		1	1.75	0.5	0.5	2	−660,810
Extreme partial combustion		1	1.5	1	0	2	−519,313

Table 1b

The equations for specific at constant pressure for various gases (equation for methane is computed from the data available at "engineeringtoolbox.com").

	Equation for specific at constant pressure (J/mol/K)
Steam	$\bar{c}_p = 143.05 - 58.040T^{0.25} + 8.2751T^{0.5} - 0.036989T$
Hydrogen	$\bar{c}_p = 56.505 - 22222.6T^{-0.75} + 116500T^{-1} - 560700T^{-1.5}$
Oxygen	$\bar{c}_p = 37.432 + 2.0102 \times 10^{-5}T^{1.5} - 178570T^{-1.5} + 2368800T^{-2}$
Carbon monoxide	$\bar{c}_p = 69.145 - 0.022282T^{0.75} - 2007.7T^{-0.5} + 5589.64T^{-0.75}$
Carbon dioxide	$\bar{c}_p = -3.7355 + 3.0529T^{0.5} - 0.041034T + 2.4198 \times 10^{-6}T^2$
Nitrogen	$\bar{c}_p = 31.308 - 0.016036T + 35.53 \times 10^{-6}T^2 - 23.322 \times 10^{-9}T^3 + 5.2048 \times 10^{-12}T^4$
Methane	$\bar{c}_p = 33.199 - 0.043401T + 228.64 \times 10^{-6}T^2 - 213.02 \times 10^{-9}T^3 + 66.116 \times 10^{-12}T^4$

$$y_1 + y_2 + y_6 = 6x_1 \quad \text{for carbon balance} \quad (3a)$$

$$2y_3 + 2y_5 + 4y_6 = 10.8x_1 + 2x_3 \quad \text{for hydrogen balance} \quad (3b)$$

$$y_1 + 2y_2 + 2y_4 + y_5 = 3.72x_1 + 0.21 \times 2x_2 + x_3 \quad \text{for oxygen balance} \quad (3c)$$

where, x_1 , x_2 and x_3 are the moles of biomass, air and water respectively and y_1 , y_2 , y_3 , y_4 , y_5 and y_6 are the number of moles of CO, CO₂, H₂, O₂, H₂O and CH₄ respectively. N₂ is not balanced because it is inert. It must be mentioned here that air in this work refers to oxygen in the air; this notation is used to distinguish O₂ in feed with unreacted O₂. Here, it must be mentioned that x_i are the inputs to the optimization problem involving Gibbs free energy minimization and y_i are the outputs.

The energy balance is given by Eq. (4).

$$\sum \dot{n}_i^{\text{out}} \int_{T_{\text{ref}}}^{T_s} C_{p,i}^{\text{out}}(T) dT = \sum \dot{n}_i^{\text{in}} \int_{T_{\text{ref}}}^{T_{\text{in}}} C_{p,i}^{\text{in}}(T) dT - \Delta H \quad (4)$$

where, $C_{p,i}$ are the specific heats of the i th component of the gas entering/leaving the unit, where i corresponds to C₆H_{10.8}O_{3.72}, H₂, O₂, CO, CO₂, CH₄, N₂ or H₂O; ΔH is the change in enthalpy due to the conversion of biomass into the various product gases.

The mathematical model for the combustion and gasification are similar with the only difference being that the inputs to combustion are biomass and oxygen, while the inputs to gasification are biomass and steam. The total Gibbs free energy of the product gases is calculated by using Eqs. (1c), (1d) and (1e) and the solution methodology is shown in Fig. 2. The change in enthalpy is calculated from the standard enthalpy of formation for the various gasification products presented in Table 2. Natural gas combustion and gasification is modelled by replacing biomass with methane on the reactants side.

Table 2

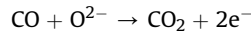
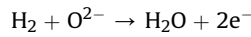
Enthalpy of formation and entropy for various gases at 298.15 K. Reproduced from Larminie and Dicks [52].

	$\bar{h}_f$ (J mol ⁻¹)	$\bar{s}$ (J mol ⁻¹ K ⁻¹)
H ₂ O (liquid)	-285,838	70.05
H ₂ O (steam)	-241,827	188.83
H ₂	0	130.59
O ₂	0	205.14
CO	-110,529	197.65
CO ₂	-393,522	213.80
CH ₄	-74,870	35.69
Biomass (assumed)	-1,300,000	

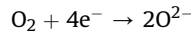
3.2. Fuel cells

SOFCS can use both CO and H₂ as fuel. These normally operate above 773 K and hence we assume that both CO and H₂ are used as fuel above a fuel cell stack temperature of 773 K and only H₂ can be used as fuel below this temperature. The reactions that occur at the anode and the cathode are given next.

The anode reactions in an SOFC:



The cathode reactions in an SOFC:



Murshed et al. [45] presented both lumped parameter model and detailed model for an SOFC system that is coupled to a methane reformer. The detailed model considers different temperatures for the electrode, interconnector and fuel and air side gases. For the purpose of the current work, we use their lumped parameter model at steady state. They have only considered H₂ fuel cells, however we consider both H₂ and CO.

Eq. (5) gives the mass balance for H₂ oxidation where $\dot{n}_{\text{H}_2}^{\text{in}}$, $\dot{n}_{\text{H}_2}^{\text{out}}$ and $\dot{n}_{\text{H}_2}^r$ are the inlet flow rate, outlet flow rate and the reaction rate of H₂ (mols⁻¹) respectively.

$$\dot{n}_{\text{H}_2}^{\text{out}} = \dot{n}_{\text{H}_2}^{\text{in}} - \dot{n}_{\text{H}_2}^r \quad (5a)$$

$$\dot{n}_{\text{H}_2}^r = 2K_r I_1 \quad (5b)$$

$$\dot{n}_{\text{H}_2}^{\text{out}} = \dot{n}_{\text{H}_2}^{\text{in}} - 2K_r I_1 \quad (5c)$$

$$I = I_1 + I_2 \quad (5d)$$

where, and $K_r = N_0/(4F)$, I is the stack current, N_0 is the number of cells in the stack and F is Faraday's constant.

Similarly, component balance equations can be written for O₂, CO, CO₂ and H₂O (Eqs. (6)–(9)).

$$\dot{n}_{\text{H}_2\text{O}}^{\text{out}} = \dot{n}_{\text{H}_2\text{O}}^{\text{in}} + 2K_r I_1 \quad (6)$$

$$\dot{n}_{\text{CO}}^{\text{out}} = \dot{n}_{\text{CO}}^{\text{in}} - 2K_r I_2 \quad (7)$$

$$\dot{n}_{\text{CO}_2}^{\text{out}} = \dot{n}_{\text{CO}_2}^{\text{in}} - 2K_r I_2 \quad (8)$$

$$\dot{n}_{\text{O}_2}^{\text{out}} = \dot{n}_{\text{O}_2}^{\text{in}} - K_r (I_1 + I_2) \quad (9)$$

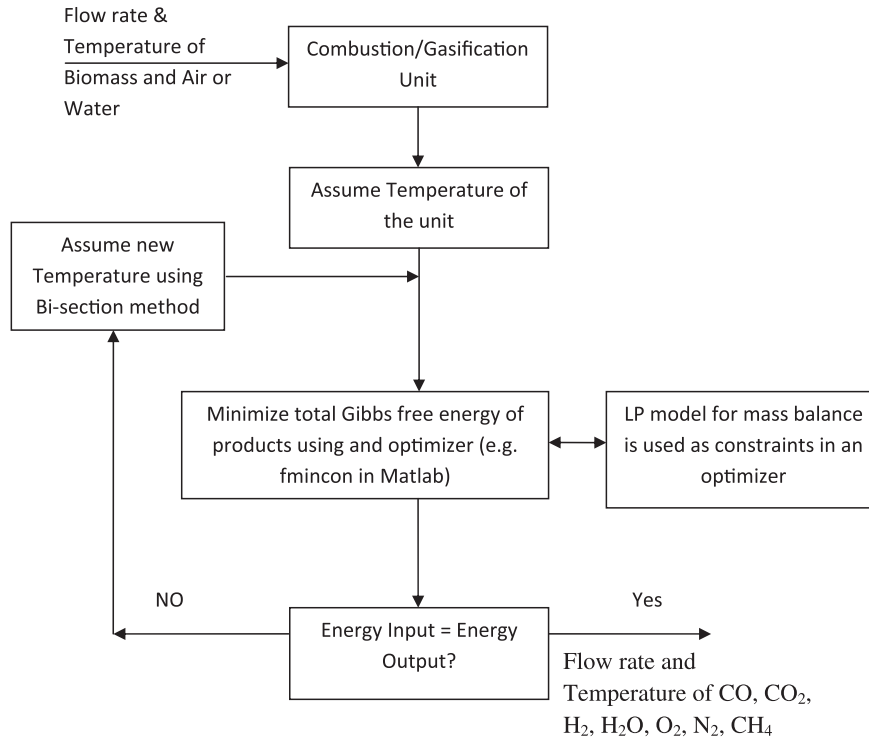


Fig. 2. Flow chart showing the solution strategy for the process of biomass combustion and biomass gasification. If stack temperature $T_s > 773$ K, both CO and H_2 are utilized, else only H_2 is utilized.

The allocation of the total current (I) is done based on the mole ratio of H_2 and CO that is present in the feed gas. It is assumed that an excess air is required for operation of the fuel cell stack. Hence, if air is insufficient, it is assumed that both reactions do not occur.

One of the key simplifications in the lumped parameter model is that the temperature across the stack is assumed to be the same. In other words, the electrodes, interconnects, electrolyte and the gases in the stack are all assumed to be at the same temperature at any given time. Then, the equation for the stack temperature T_s can be obtained by a simple energy balance across the stack.

$$\sum \dot{n}_i^{\text{out}} \int_{T_{\text{ref}}}^{T_s} C_{p,i}(T) dT = \sum \dot{n}_i^{\text{in}} \int_{T_{\text{ref}}}^{T_{\text{in}}} C_{p,i}(T) dT - \Delta H - V_s I \quad (10)$$

where, $C_{p,i}$ and $C_{p,o}$ are the specific heat of the i th component of the gas (H_2 , O_2 , CO, CO_2 or H_2O) entering/leaving the fuel cell stack. ΔH is the change in enthalpy for the hydrogen and CO oxidation reactions and V_s is the stack voltage.

The stack voltage in the fuel cell can be calculated from the various losses (η_{ohm} , η_{act} , η_{con} – ohmic, activation and concentration losses) and the open circuit voltage ($V_o = V_o^C + V_o^H$) (Eq. (11)).

$$V_s = V_o^C + V_o^H - \eta_{\text{ohm}} - \eta_{\text{act}} - \eta_{\text{con}} \quad (11)$$

Briefly, ohmic losses are caused by the resistance of electrolyte to ions and it changes linearly with current density; activation losses occur due to the energy spent to drive the ions between the electrodes (it is usually more at the cathode) and is predominant at low current density; and concentration losses occur due to the unavailability of the reactants and is predominant at high current density.

The open circuit voltage for hydrogen oxidation V_o^H is given by Eq. (12).

$$V_o^H = N_o \Delta E = N_o \left[\Delta E_o + \frac{RT_s}{2F} \ln \frac{p_{H_2} p_{O_2}^{0.5}}{p_{H_2O}} \right] \quad (12)$$

where, the standard cell potential ΔE_o changes linearly with stack temperature and is approximated as in Eq. (13).

$$\Delta E_o \text{ (V)} = 1.2586 - 0.000252 T_s \text{ (K)} \quad (13)$$

Similar equations for carbon monoxide oxidation are required and this is given by Eq. (14).

$$V_o^C = N_o \Delta E = N_o \left[\Delta E_o + \frac{RT_s}{2F} \ln \frac{p_{CO} p_{O_2}^{0.5}}{p_{CO_2}} \right] \quad (14)$$

In this work, the pressure term in Eq. (14) is neglected (assumed to be equal to 1). The value of ΔE_o can be calculated from Eq. (15)

$$\Delta E_o = \frac{-\Delta g_f}{nF} \quad (15)$$

where F is the Faraday constant and n is the number of electrons participating in the CO oxidation reaction ($n = 2$ in this case). The equation for change in molar Gibbs free energy of formation (Δg_f) for the reaction can be derived from the data given by Larminie and Dicks [62]. The values of change in Gibbs energy of formation (Δg_f) with temperature for CO are given in Table 3.

It can be shown that

$$\Delta E_o \text{ (V)} = 1.4736 - 0.005 T_s \text{ (K)} \quad (16)$$

Murshed et al. [45] only considered Ohmic losses in their work. Here, we also consider concentration losses. For simplicity, activation losses not considered as they involve pressure terms. Ohmic losses are given by Eq. (17).

Table 3

Sample values of Δg_f for carbon monoxide oxidation. Reproduced from Larminie and Dicks [52].

Temperature (°C)	Δg_f (kJ mol ⁻¹)
100	-250.7
300	-232.7
500	-214.6
700	-196.5
900	-178.5

$$\eta_{ohm} = r(T_s)I \quad (17)$$

The cell resistance $r(T_s)$ is given by the second order Steinhart–Hart equation as

$$r(T_s) = r_o \exp \left[\alpha \left(\frac{1}{T_s} - \frac{1}{T_o} \right) \right] \quad (18)$$

where r_o (Ω) is the internal resistance at temperature T_o (K) and α is a constant.

The concentration losses are given by Eq. (19).

$$\eta_{con} = \frac{RT_s}{2F} \ln \left(1 - \frac{I}{I_L} \right) \quad (19)$$

Table 4

The ratio of specific heat at constant pressure to specific heat constant volume of various gases considered here.

	γ
Air	1.4
CO	1.4
CO ₂	1.28
H ₂	1.4
O ₂	1.41
H ₂ O	1.33
CH ₄	1.32
N ₂	1.4

where I_L is the limiting current, r_o is 0.126 Ω and α is 2870 [45]. The solution methodology for the energy balance in fuel cells is shown in Fig. 3.

3.3. Gas turbine

The gas turbine consists of a compressor, a combustion chamber and a turbine. The compressor and the turbine are connected either through a single shaft or through two shafts connected through a gear box. The speeds of compressor and turbine in a single shaft MGT are the same. In a dual shaft MGT the speeds can be different. Single shaft MGTs come in both fixed speed and variable speed

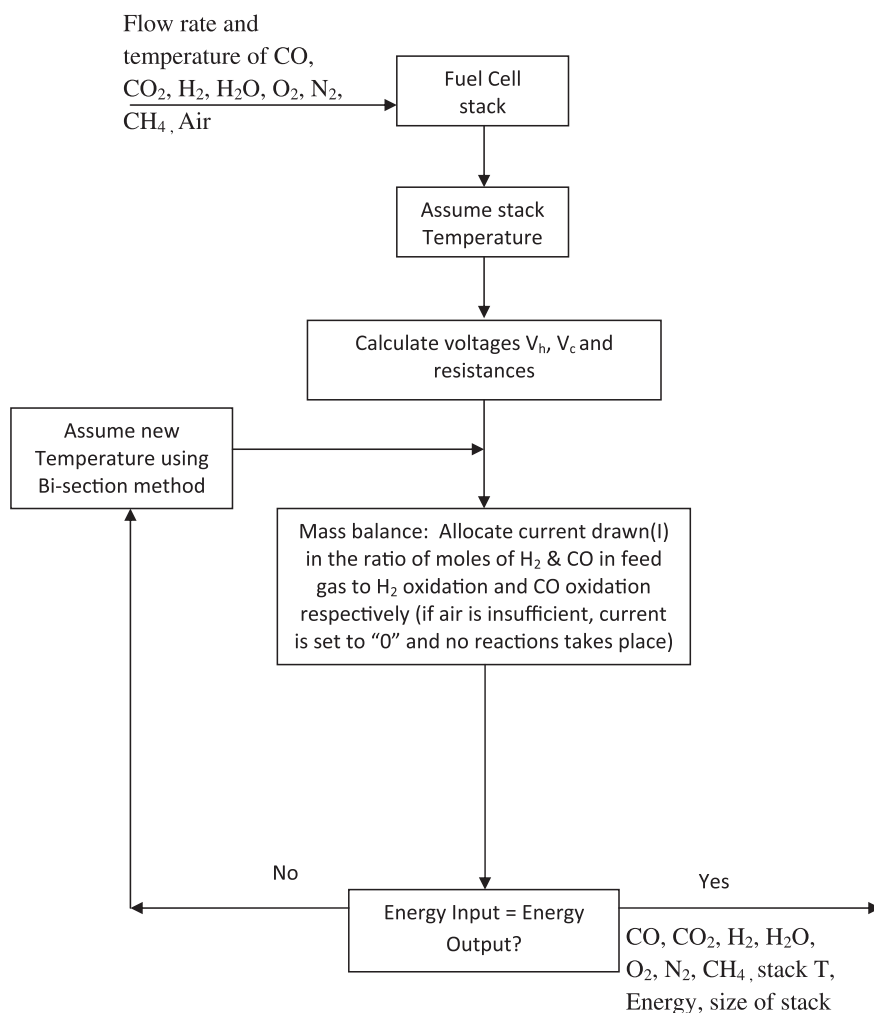


Fig. 3. Flow chart showing the solution strategy for energy balance of fuel cells.

configurations. The compressor supplies air at high pressure to the combustion chamber. The spent gases from the combustion chamber expand in a turbine, generating electricity. The equation for the change in temperature across the compressor is given by Eq. (20).

$$T_2 - T_1 = \frac{T_1}{\eta_c} \left[\left(\frac{p_2}{p_1} \right)^{(\gamma-1)/\gamma} - 1 \right] \quad (20)$$

where, γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume, p_1 and T_1 are the pressure and temperature at the inlet to the compressor while p_2 and T_2 are those at the outlet. η_c is the isentropic efficiency of the compressor. The individual values of γ are given in Table 4 and the γ of a gas stream is calculated as the (mole) weighted average of the components in the stream. It must be noted that γ is temperature dependent; however we assume that γ is constant as is common in literature on gas turbines. The equation for the change in temperature across the turbine is given by Eq. (21).

$$T_3 - T_4 = \eta_t T_3 \left[1 - \left(\frac{1}{p_3/p_4} \right)^{(\gamma-1)/\gamma} \right] \quad (21)$$

where, η_t is the isentropic efficiency of the turbine, p_3 and T_3 are the pressure and temperature at the inlet to the turbine while p_4 and T_4 are those at the outlet.

Ideally, the model for minimization of Gibbs free energy must be used to represent the combustion chamber of the gas turbine. From Fig. 1, it can be seen that the superstructure has seven gas turbines. Hence nine optimization problems (including combustion and gasification) involving Gibbs free energy minimization need to be solved. However, this adds considerable computational time. In view of this, it is assumed that if excess air is available in the combustion chamber, fuel utilization is 90%. If less air is available, fuel utilization is assumed to be in the range of 0–90% depending on the amount of air available. Thus we only solve two optimization problems (combustion and gasification) involving Gibbs free energy minimization. Knowing the mass balance from the extent of fuel utilization, the temperature of the gases exiting the combustion chamber is obtained using bi-section method to check for energy balance.

A compressor/turbine map gives the isentropic efficiency when the pressure ratio and the shaft speed are known. For the purpose of this work, we only consider a single shaft gas turbine which means that the compressor and the turbine both run at the same speed.

The energy required to drive the compressor and the energy generated by the turbine (per unit mass) is given by Eq. (22).

$$W_c = \frac{(C_p^2 T_2 - C_p^1 T_1)}{\eta_s^c} \quad (22a)$$

$$W_t = \eta_s^t (C_p^3 T_3 - C_p^4 T_4) \quad (22b)$$

where, η_s^c and η_s^t are the shaft efficiencies of compressor and turbine, respectively, and C_p^i is the average specific heat at constant pressure of the gas at the corresponding temperature. The average specific heat is the (mole) weighted average of components of the gases mixture.

It is common to use compressor charts and look-up tables to calculate the speed and efficiency of the compressor when the flow rate and pressure ratio are given. However, only the best steady state conditions are required for the design problem, it is assumed

that the compressor and turbine operate at a pressure ratio of 3 and a compression/expansion efficiency of 0.95 and shaft efficiency of 0.9.

Gas turbines are sometimes equipped with a regenerator/recuperator (for heat recovery). In the current superstructure, the spent gases are not directly sent to the atmosphere, but are sent to the next unit. In view of this, we do not consider a heat recovery directly at the gas turbine, but consider the same after all the units by using a simple model of the heat recovery. That is, we consider that the spent gases from the fuel cell stack or gas turbine can be used to extract energy in a Heat Recovery unit that comes downstream to the superstructure (Fig. 1). It is assumed that the range of operation of the Heat Recovery unit is between 673 K and 393 K (corresponding to Lower Heating Value). The spent gases are at a high temperature and the losses are primarily due to heat exchanger and rotating equipment. A heat exchanger efficiency of about 70% was considered by others [63] and we assume further losses for rotating equipment and consider a net efficiency of 65% for heat recovery.

3.4. Multi-objective optimization using genetic algorithm

We briefly explain genetic algorithms and the readers are referred to literature for a detailed presentation on genetic algorithms [61,64]. The concept of genetic algorithms has their roots in biology and is based on crossovers and mutations of chromosomes. In an optimization problem, a chromosome is a set of decision variables that are used to calculate one or more objective functions. A set of chromosomes is called a population. Two chromosomes participate in crossovers and one or more off springs are produced. A single chromosome undergoes mutation and one offspring is produced. We begin solving the optimization problem with *NEW-population* and through random crossovers and mutations, end it with the *FINAL-population*. The *FINAL-population* consists of the parent and offspring chromosomes. Of late, there are several types of crossovers and mutations that are proposed and the readers can know more about the same in the references provided [61,64]. In MOO, two chromosomes are said to be non-dominated if neither is better than the other in all the objectives that are considered. Using the criteria of non-domination, an *ND-population* can be shortlisted from the *FINAL-population*. If the objective values are plotted on a 2D plot (for a two objective problem) or 3D plot (for a three objective problem), the Pareto front (curve for 2D plot and surface for 3D plot) can be visualized.

In this work we use two objectives: one is the energy generated by fuel cells while the other is the energy generated by the gas turbines. The superstructure optimization using MOO allows us to obtain designs that are a combination of fuel cell topping cycle and fuel cell bottoming cycle. The analysis of the Pareto front [64] gives us new designs and the decision maker can select a design that best suits the requirement. It is obvious that the system with only fuel cells would fall at one end of the spectrum while that with only gas turbines would fall at the other end of the spectrum and any new design will have both the fuel cells and gas turbines.

For the purpose of this work, the single objective optimization algorithm of Naraharisetti et al. [61] is developed into a multi-objective optimization algorithm by introducing concepts of non-dominated sorting and crowding distance [64]. Further, the algorithm was modified to allow random number of crossovers and mutations in each generation instead of the usual fixed number of crossovers and mutations. Briefly, the set consisting of the initial population and the chromosomes obtained through different types of crossovers and mutations (*FINAL-population*) is sorted based on the concept of non-domination to obtain the new set (*ND-population*). In non-dominated sorting a given chromosome is said to be

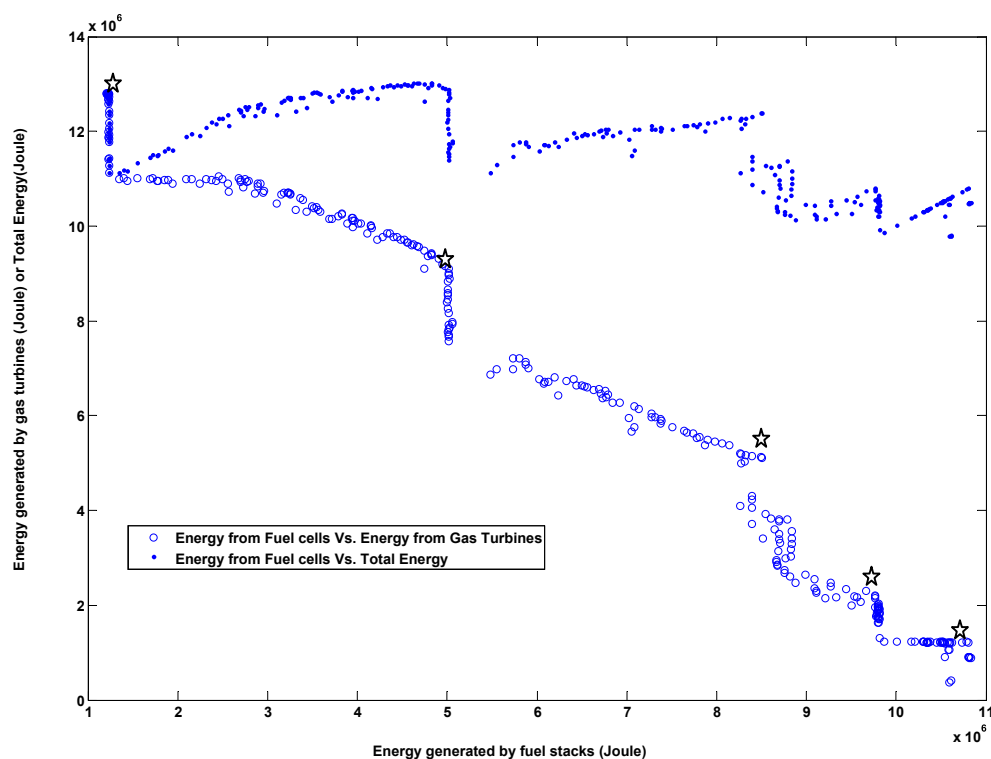


Fig. 4. The Pareto plot of the First Set of Solutions when biomass is used (constraint on capacity of unit = min 10% of Total Energy). The locations of the five different networks are shown by star. Amount of CO at Gibbs equilibrium = 80% (rest of the CO is combusted).

non-dominated if it satisfies the criteria for non-domination with respect to all the other chromosomes. However, in this work, a chromosome is included in the *NDpopulation* if it dominates only 98% of the chromosomes. The *NDpopulation* is sorted further using the concept of crowding distance. The members of the *NDpopulation* are sorted in descending order using the first objective. The maximum and minimum of the first objective are used to generate a scale having n equal intervals (between the maximum and the minimum), where n is equal to half the population size. All chromosomes from *NDpopulation* will fall in some interval or the other in this scale; from each interval only one chromosome (having the best objective in that interval) is selected and placed in the new set (*NEWpopulation*). The same is done using the second objective to get the complete *NEWpopulation*. If the size of the *NEWpopulation* is less than the population size, chromosomes are randomly taken from the *FINALpopulation* and added to *NEWpopulation*.

The superstructure has one combustion unit, one gasification unit, seven fuel cell stacks and seven gas turbines (Fig. 1). The decision variables in the optimization problem are: Air supply to combustion unit (1 nos.), gasification unit (1 nos.), fuel cell stacks (7 nos.) and gas turbines (7 nos.); water supply to gasification unit (1 nos.); number of fuel cells in each fuel cell stack (7 nos.); and ratio of gas flow that is split between the fuel cell stack and gas turbine at each junction (7 nos.). Hence, there are a total of 31 decision variables (chromosome length = 31) for the genetic algorithm to optimize. In addition, each sub-optimization problem (combustion, gasification and fuel cell stack) has their own decision variables. Further, it is assumed that a constant current of 100A is drawn from the fuel cell stacks.

A population size of 20 times the length of the chromosome is considered in the genetic algorithm (population size = 620) and the genetic algorithm is run for three days. Each function evaluation takes 1.125 s and the algorithm spends 98% of the time in function evaluations (including mutations and crossovers) and 2%

of the time in sorting and moving from one generation to the next. Here, each function evaluation refers to the calculation of the energy generated by a given network; it includes the optimization of combustion/gasification processes. Hence, a total of about 225k function evaluations are performed before the algorithm terminates. The algorithm is run twice and the best values are reported. The model and genetic algorithm are implemented in Matlab R2009b and the operating system is Windows XP Professional. The computer hardware is as follows: HP Compaq 6000 Pro SFF PC with Intel Core 2 Duo CPU E8400 @ 3.00 GHz with 3544 MB RAM.

Once the MOO is completed (after 3 days of run time), multiple optimal designs are identified via a two-step procedure. The Pareto front (Fig. 4–10) from the MOO is analyzed manually and the various designs are picked. These designs are from the vertices that are marked in the figures. We have observed that the operational conditions vary as we move away from the vertex and the underlying design around a vertex remains the same. Although the MOO optimizes the operational variables also, each individual design is optimized further (3 h) using the single objective optimization algorithm to see if any improvements in operating conditions can be made. It must be noted here that the single objective optimization does not eliminate any designs because the superstructure optimization is already complete.

4. Results and discussion

For the purpose of this work, it is assumed that biomass has a general formula of $C_6H_{10.8}O_{3.72}$ which is that of empty fruit bunches. A biomass flow of 1 kg/s (7.03 mol/s) each to the combustion unit and gasification unit is considered as the basis of design for the system under consideration. The combustion gases are fed through the gasification unit; hence a maximum of 84.3 mol/s of a mixture CO and CO_2 will exit the gasification unit.

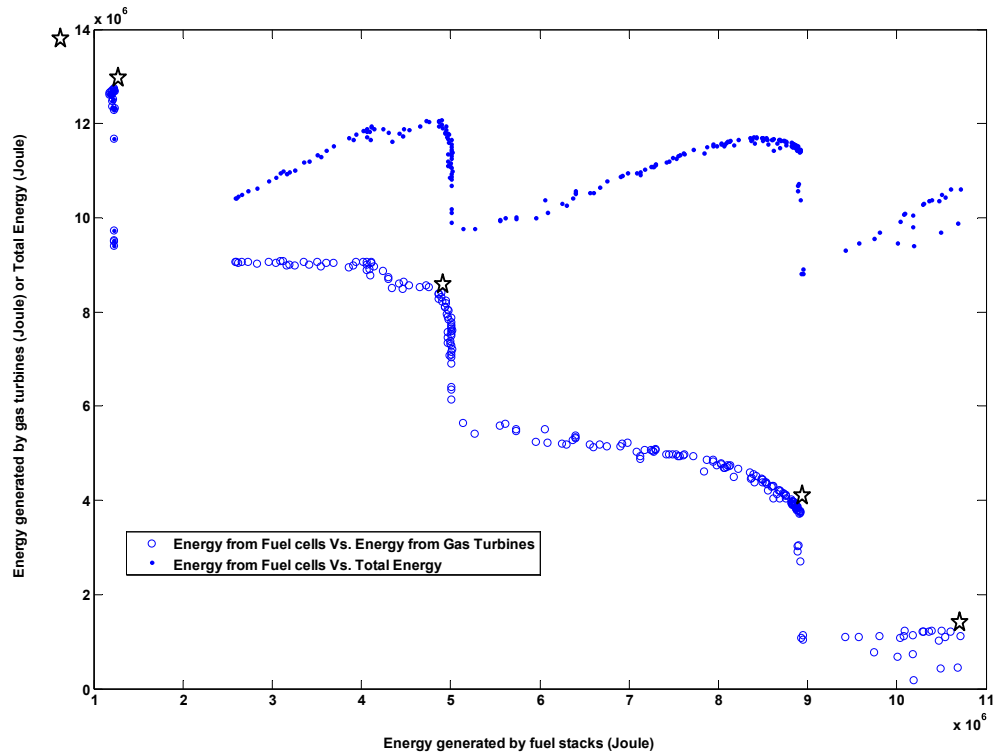


Fig. 5. The Pareto plot of the second set of solutions when biomass is used (constraint on capacity of unit = min 20% of total energy). The locations of the four different networks are shown by the star. Amount of CO at Gibbs equilibrium = 80% (rest of the CO is combusted).

Complete combustion releases 84.3 mol/s of CO_2 and no CO, while extreme partial combustion releases 84.3 mol/s of CO and no CO_2 . It is not practical to assume that the combustion and gasification units operate at Gibbs equilibrium, hence we arbitrarily assume

that 20% of the CO generated at Gibbs equilibrium gets converted to CO_2 . From Table 2, the energy content of biomass can be derived as 2.367 MJ/mol when biomass undergoes total combustion. Hence, 2 kg/s of biomass will have the ability to generate 33.28 MW of

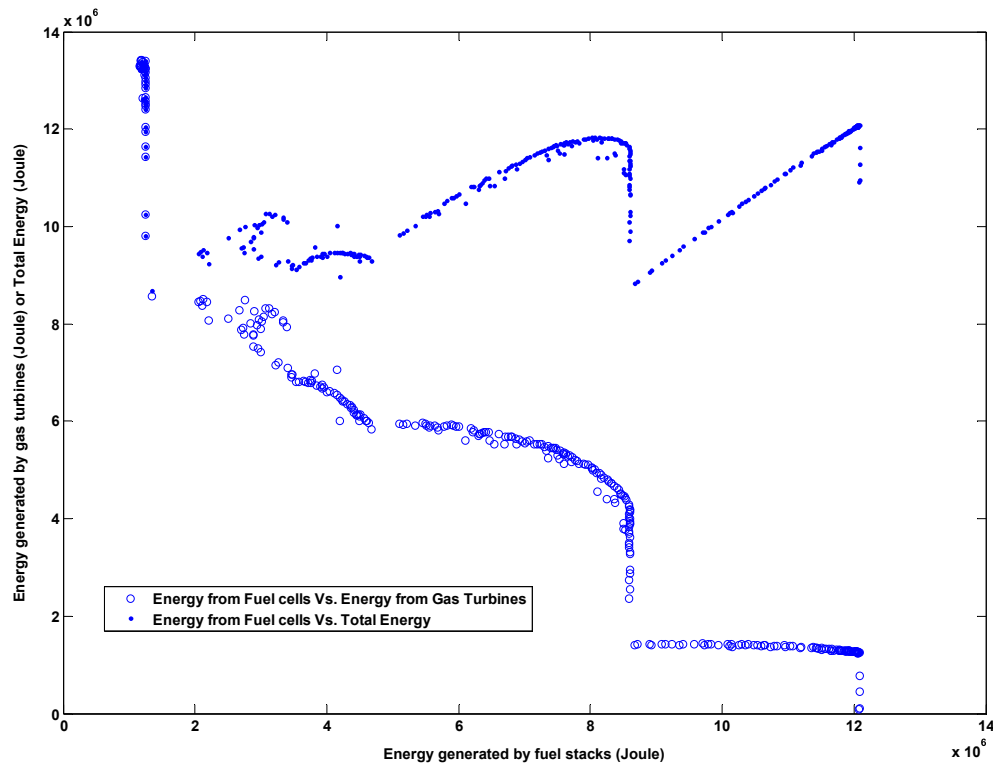


Fig. 6. The Pareto plot of the second set of solutions when biomass is used (constraint on capacity of unit = min 20% of total energy). Amount of CO at Gibbs equilibrium = 90% (rest of the CO is combusted).

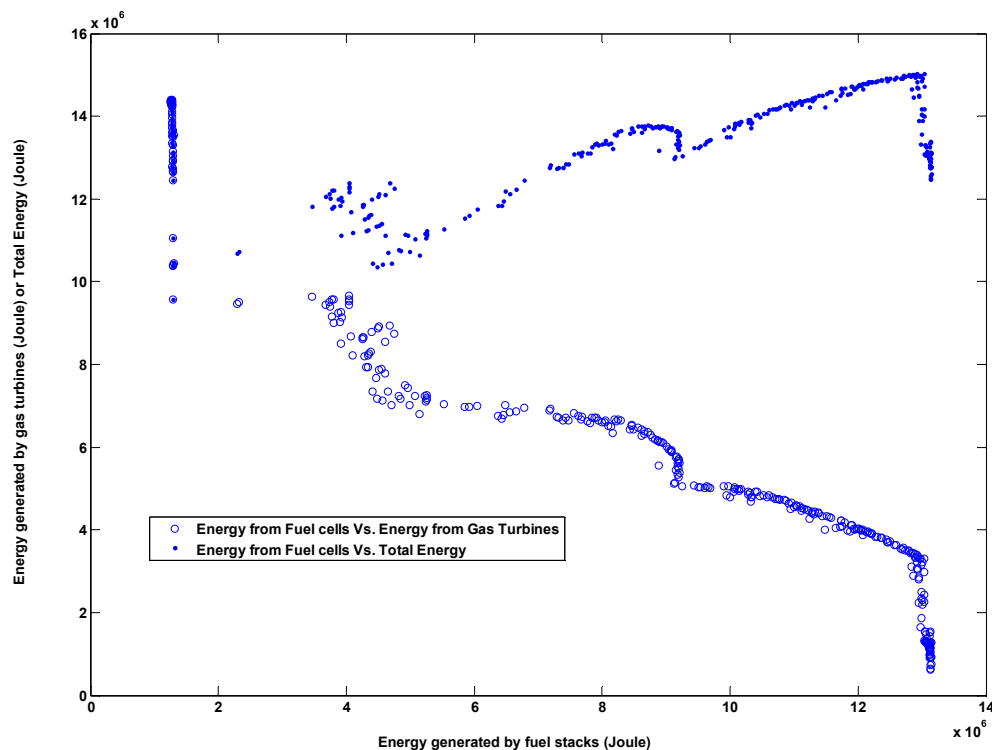


Fig. 7. The Pareto plot of the second set of solutions when biomass is used (constraint on capacity of unit = min 20% of total energy). Amount of CO at Gibbs equilibrium = 100% (extreme partial combustion).

energy, i.e., the capacity of the system with biomass as the fuel is 33.28 MW. The capacity of the biomass based power plant is of order as has been recommended by other researchers [65]. Here, it may be noted that the system achieves economies of scale in the

range of 30–50 MW. The CapEx changes linearly with capacity once a system achieves economies of scale. In view of this, neglecting CapEx in our superstructure would not greatly skew the results since we are in the range mentioned in the reference.

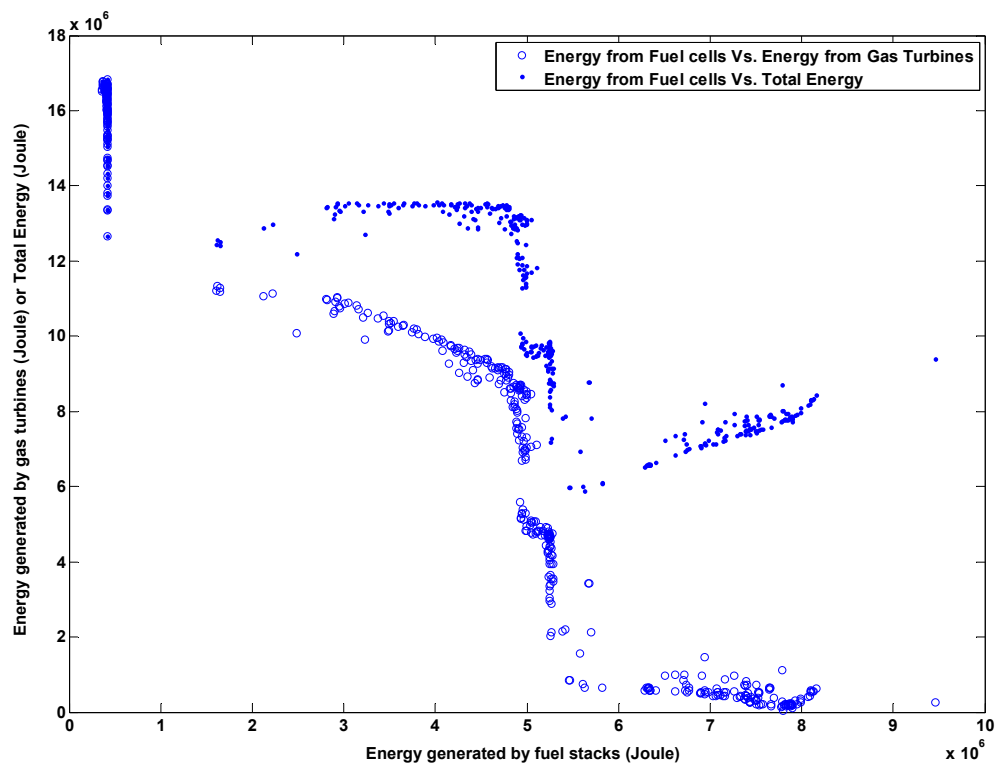


Fig. 8. The Pareto plot when natural gas is the fuel (constraint on capacity of unit = min 20% of total energy). Amount of CO at Gibbs equilibrium = 80% (rest of the CO is combusted).

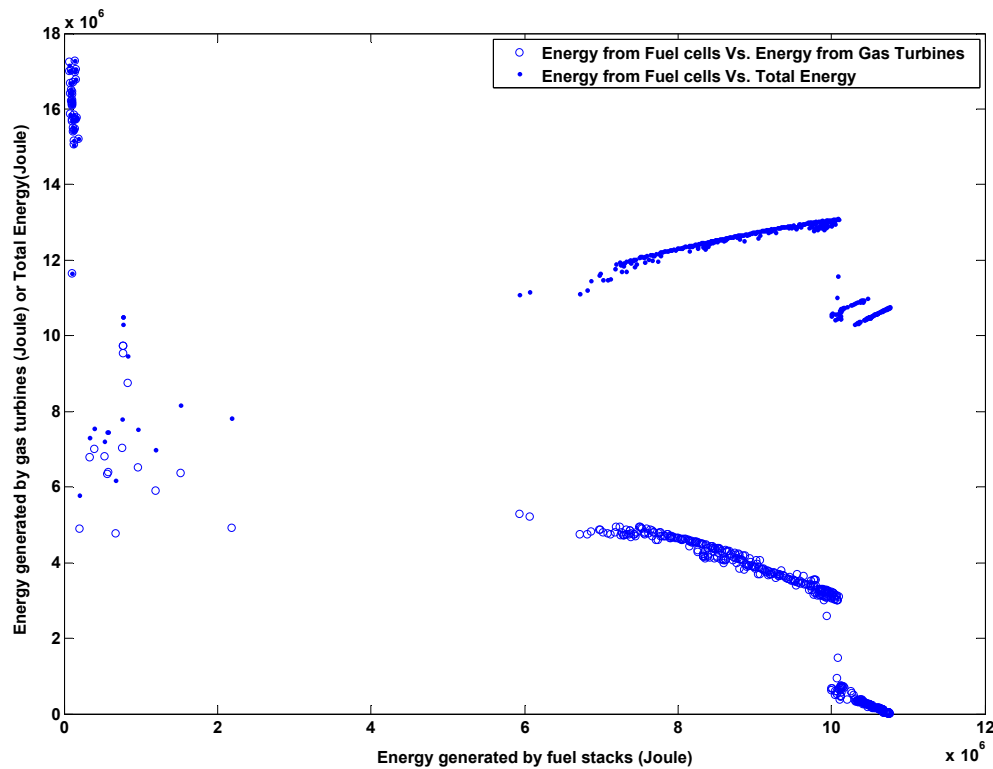


Fig. 9. The Pareto plot when natural gas is the fuel (constraint on capacity of unit = min 20% of total energy). Amount of CO at Gibbs equilibrium = 90% (rest of the CO is combusted).

The network superstructure has 14 units and the optimization algorithm may give results suggesting fourteen units in the plant with several of them producing small amounts of energy. Such a solution is not practical; hence a constraint on the size of individual

units is necessary. Two different constraints are implemented and the results are discussed later. Before we analyze these two constraints, we make some observations based on an understanding of thermodynamics.

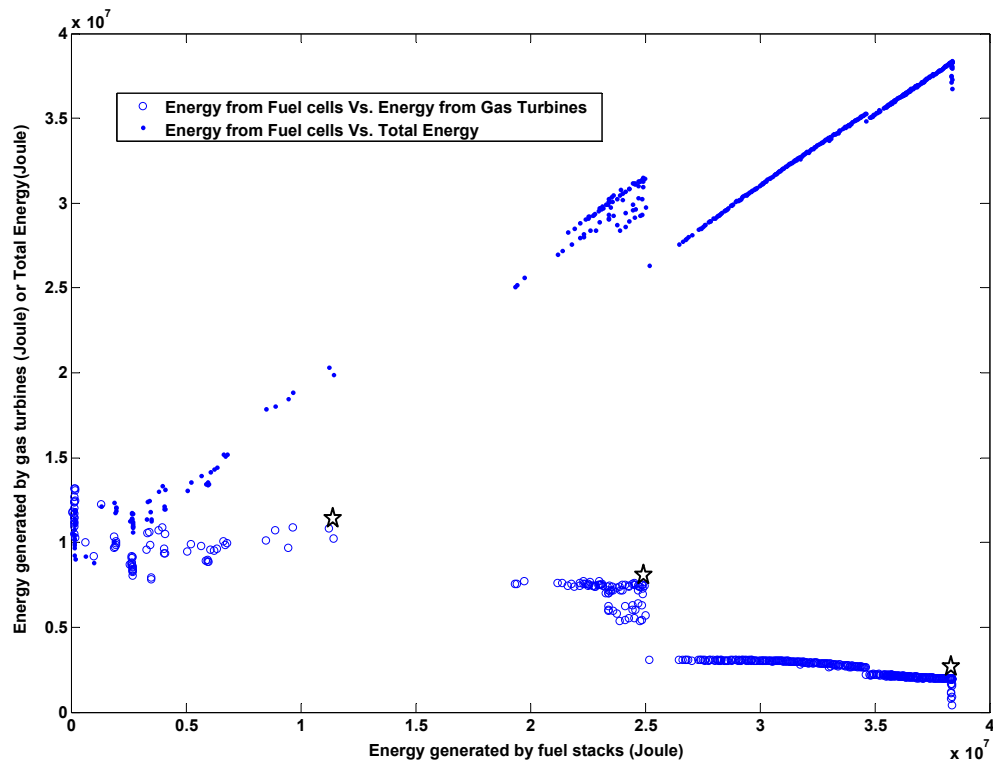


Fig. 10. The Pareto plot when natural gas is the fuel (constraint on capacity of unit = min 20% of total energy). The locations of the three different networks are shown by star. Amount of CO at Gibbs equilibrium = 100% (extreme partial combustion).

Table 5

Mass balance and energy generated by different units for the first set of solutions.

	C	G	FC_G	GT_G	FC_GF	GT_GF	GT_GG	FC_GFF	GT_GFF	GT_GFG	GT_GGG
Network 1											
CO-in (mole)		33.7		67.5			34.6				3.5
CO-out (mole)	33.7	67.5		34.6			3.5				0.4
CO ₂ -in (mole)		8.4		16.9			49.7				80.9
CO ₂ -out (mole)	8.4	16.9		49.7			80.9				84.0
Exit <i>T</i> (K)	995	1022		1465			1473				915
Energy (MW)				3.91			4.95				3.60
Network 2											
CO-in (mole)		33.7	67.5		25.6	16.0			1.3	1.6	
CO-out (mole)	33.7	67.5	41.6		1.3	1.6			0.1	0.2	
CO ₂ -in (mole)		8.4	16.9		26.3	16.4			50.6	30.8	
CO ₂ -out (mole)	8.4	16.9	42.8		50.6	30.8			51.8	32.3	
Exit <i>T</i> (K)	1124	971	954		1000	1448			724	919	
Energy (MW)			4.37		3.98	1.56			1.35	1.38	
Network 3											
CO-in (mole)		33.7	17.1	33.3		8.3	16.9			1.1	1.7
CO-out (mole)	33.7	67.5	8.3	16.9		1.1	1.7			0.1	0.2
CO ₂ -in (mole)		8.4	4.3	8.3		34.5	24.7			41.6	39.9
CO ₂ -out (mole)	8.4	16.9	34.5	24.7		41.6	39.9			42.6	41.4
Exit <i>T</i> (K)	995	1022	1040	1471		1097	1463			715	942
Energy (MW)			4.13	1.94		1.41	2.44			1.33	1.74
Network 4											
CO-in (mole)		33.7	67.5		42.2			7.5	8.5		
CO-out (mole)	33.7	67.5	42.2		16.1			0.0	0.8		
CO ₂ -in (mole)		8.4	16.9		42.1			31.8	36.0		
CO ₂ -out (mole)	8.4	16.9	42.1		67.8			41.5	41.5		
Exit <i>T</i> (K)	1008	1028	915		959			1013	833		
Energy (MJ)			4.36		4.36			1.29	1.56		
Network 5											
CO-in (mole)		33.7	67.5		46.7			24.7			
CO-out (mole)	33.7	67.5	46.7		24.7			1.7			
CO ₂ -in (mole)		8.4	16.9		37.6			59.6			
CO ₂ -out (mole)	8.4	16.9	37.6		59.6			82.6			
Exit <i>T</i> (K)	995	1022	934		934			966			
Energy (MJ)			3.54		3.15			3.85			

1. Extreme high temperatures are detrimental to the operation of fuel cells both in terms of stability of material and fuel utilization. Hence, we limit the operating temperature of the fuel cell stacks at 1200 °C.
2. Gas turbines are more efficient at higher temperatures. Hence, it may be possible that the gas turbine network can produce about the same amount of energy as the fuel cell only network and the same was observed when biomass is used as fuel (Sections 4.1–4.3).
3. The fuel utilization in a fuel cell stack will never be 100% (particularly at higher temperatures). In view of this, an after burner/gas turbine is required to extract more energy from the fuel cell exhaust gases. It follows that the operating temperature of this gas turbine would be lower than that of the fuel cell stack. It was observed that fuel cell topping networks are more efficient than gas turbine topping networks when natural gas is used as fuel (Section 4.4).

4.1. Constraint I

In the first case, it is assumed that the energy generated by any unit must be at least 10% of the total energy produced by the network. This limits the total number of units to ten. The Pareto plot (Energy from Fuel Cell stack on *x*-axis and that from gas turbine on *y*-axis) generated by using the MOO is shown in Fig. 4. It can be seen

from the plot that there are different clusters. Different networks are chosen from each of the vertices of the Pareto front (represented by star in Fig. 4) and the details are presented in Table 5. Networks 1 and 5 are gas turbine only and fuel cell only networks respectively while the others have both fuel cell stacks and gas turbines. It can be seen from the other networks that the fuel cells stacks are fairly large in capacity compared to the gas turbines; also the number of gas turbines is large compared to that number of fuel cell stacks. It is easy to implement several fuel cell stacks in different sizes; however the same is not true for gas turbines. In view of this, this set of networks has little practical importance.

4.2. Constraint II

Here, it is assumed that the energy generated by any unit must be at least 20% of the total energy produced by the network. This limits the total number of units to five. The Pareto plot (Energy from Fuel Cell stack on *x*-axis and that from gas-turbine on *y*-axis) generated by using the MOO is shown in Fig. 5. It can be seen from the plot that there are different clusters. Different networks are chosen from each of the vertices of the Pareto front (represented by star in Fig. 5) and the details are presented in Table 6. Networks 6 and 9 are gas turbine only and fuel cell only networks respectively while the others have both fuel cell stacks and gas turbines. It can be seen that the networks have only three units making them good candidates if an actual system is built. Further, it can be seen that

Table 6

Mass balance and Energy generated by different units for the second set of solutions.

	C	G	FC_G	GT_G	FC_GF	GT_GF	GT_GG	FC_GFF	GT_GFF	GT_GFG	GT_GGG
Network 6											
CO-in (mole)		33.7		66.1			35.6				3.6
CO-out (mole)	33.7	66.1		35.6			3.6				35.6
CO ₂ -in (mole)		6.7		13.2			43.8				75.8
CO ₂ -out (mole)	6.7	13.2		43.8			75.8				79.0
Exit T (K)	1035	1103		1470			1463				908
Energy (MW)				3.91			5.06				3.64
Network 7											
CO-in (mole)		33.7	66.1			41.9				10.5	
CO-out (mole)	33.7	66.1	41.9			10.5				1.1	
CO ₂ -in (mole)		6.7	13.2			37.4				68.8	
CO ₂ -out (mole)	6.7	13.2	37.4			68.8				78.3	
Exit T (K)	1022	1117	1089			1473				1012	
Energy (MW)			3.73			3.85				3.89	
Network 8											
CO-in (mole)		33.7	66.1		40.2				14.3		
CO-out (mole)	33.7	66.1	40.2		14.3				1.4		
CO ₂ -in (mole)		6.7	13.2		39.1				65.0		
CO ₂ -out (mole)	6.7	13.2	39.1		65.0				77.9		
Exit T (K)	1184	1059	903		976				811		
Energy (MW)			4.51		4.31				2.99		
Network 9											
CO-in (mole)		33.7	66.1		45.4			23.0			
CO-out (mole)	33.7	66.1	45.4		23.0			13.4			
CO ₂ -in (mole)		6.7	13.2		33.9			56.3			
CO ₂ -out (mole)	6.7	13.2	33.9		56.3			79.3			
Exit T (K)	1119	1080	990		900			948			
Energy (MW)			3.41		3.91			3.89			

Networks 1 and 6 are similar (gas turbine only networks) and Networks 5 and 9 are similar (fuel cell only networks) in terms of the amount of energy generated by each unit. The total amount of energy generated by each network is given in Table 8a.

From both the set of solutions, it is clear that different networks can generate about the same amount of energy. At the onset of this work, we set out to find the optimal type of network (fuel cell topping/bottoming). From Tables 5 and 6, it can be seen that fuel cell topping cycles are predominant. The only different network is Networks 3 where both fuel cell stack and gas turbine are at the same level (neither fuel cell topping nor fuel cell bottoming); however this network has no practical significance because the number of gas turbines is large and the capacity of each gas turbine is small in comparison to fuel cell stacks. In view of this, we conclude that any one of fuel cell only network, gas turbine only network or a fuel cell topping network can be chosen based on the practical considerations and local needs.

4.3. Effect of partial combustion of CO

In the earlier examples, we assumed that 20% of the generated CO at Gibbs equilibrium gets converted to CO₂. This resulted in networks where the gas turbine only network generates more energy than the fuel cell only network. In view of this the effect of amount of CO that is converted into CO₂ on the energy generation is studied. Briefly, two networks where the amount of CO that is converted to CO₂ is 10% and 0% are analyzed and the results are shown in Figs. 6 and 7. It can be seen that as the amount of CO that is converted to CO₂ in the combustion/gasification units is reduced, the amount of energy generated by the fuel cell only networks increases. However, even when the system is operated without any deviation from Gibbs equilibrium the amount of energy generated by fuel cells only network is less than that generated by the gas

turbine only network. In view of this, it is important to analyze the effect of co-firing of biomass with other fuels so as to exploit the full potential of fuel cells.

4.4. Use of natural gas as fuel

Since it was observed that fuel cell only design, gas turbine only design and fuel cell topping design can all generate about the same amount of energy when biomass is used as fuel, we study the effect of using natural gas as fuel. Briefly, three cases where the amount of CO that is converted to CO₂ is 0%, 10% and 20% are analyzed using the optimization procedure described earlier. To have a basis for comparison, we consider that the total flow of natural gas to the combustion unit and the gasification unit is 84.36 mol/s (same number of moles of carbon as that when biomass is used) and the results from the optimization of the three cases are shown in Figs. 8–10. From Table 2, the energy content of natural gas can be derived as 0.8 MJ/mol at total combustion. Hence, 84.36 kg/s of biomass will have the ability to generate 67.68 MW of energy, i.e., the capacity of the system with natural gas as the fuel is 33.28 MW. It can be seen from Figs. 8 and 9 that the amount of energy generated by the fuel cell only networks is lower than the energy generated by the gas turbine only network when 10% or 20% of the CO is converted to CO₂. However, when the entire CO is maintained at Gibbs equilibrium, the fuel cell networks generated more than double the energy generated by the gas turbine only networks.

Three different networks (Networks A–C) from the optimization of the superstructure when natural gas is used as the fuel (and the combustion/gasification units are maintained at Gibbs equilibrium) are shown in Table 7. The total amount of energy generated by each network is given in Table 8b. It can be seen clearly that the fuel cell only network generates more energy than the other networks and that the next highest energy is generated by the fuel cell topping

Table 7

Mass balance and Energy generated by different units when natural gas is used as fuel.

	C	G	FC_G	GT_G	FC_GF	FC_GG	GT_GF	GT_GG	FC_GFF	FC_GFG	FC_GGF	FC_GGG	GT_GFF	GT_GFG	GT_GGF	GT_GGG
Network A																
CO-in (mole)		84.3	84.3			57.7						27.0				
CO-out (mole)	84.3	84.3	57.7			27.0						0.0				
CO ₂ -in (mole)		0.0	0.0			26.7						57.3				
CO ₂ -out (mole)	0.0	0.0	26.7			57.3						84.3				
Exit T (K)	873	873	783			785						903				
Energy (MW)			13.23			15.18						12.84				
Network B																
CO-in (mole)		84.3	84.3			57.1						26.4				
CO-out (mole)	84.3	84.3	57.1			26.4						2.6				
CO ₂ -in (mole)		0.0	0.0			27.2						57.9				
CO ₂ -out (mole)	0.0	0.0	27.2			57.9						81.7				
Exit T (K)	908	883	879			973						1454				
Energy (MW)			12.81			13.91						6.7				
Network C																
CO-in (mole)		84.3		84.3			68.3				59.1					
CO-out (mole)	84.3	84.3		68.3			59.1				21.2					
CO ₂ -in (mole)		0.0		0.0			15.4				22.9					
CO ₂ -out (mole)	0.0	0.0		15.4			22.9				60.5					
Exit T (K)	873	873		1364			1352				1440					
Energy (MW)				4.69			4.66				13.34					

network. From Tables 8a and 8b, it can be seen that maintaining the combustion/gasification units at Gibbs equilibrium and using natural gas as fuel helps generate energy at a higher energy (above 50%) when compared to using biomass.

Hence, we conclude that natural gas is the preferred fuel over biomass when fuel cells are used and that it is of utmost importance to maintain the process at Gibbs equilibrium for maximum energy production. If maintaining the combustion and gasification units at Gibbs equilibrium is operationally difficult, then gas turbines must be preferred over fuel cells. It may be noted here that others [66] have also observed that natural gas based IGFCs have higher efficiency compared to biomass based IGFCs.

4.5. Comparison with literature

It is common to set up a simulation program and study the effect of each variable on the performance of a system. Such a rigorous study based on enumeration would work well when the number of variables is small. As the number of variables increases, the efficacy of the system largely depends on the choices that the designer makes on what values the variables take. For linear systems, this would give meaningful results, however when the degree of nonlinearity increases, enumeration would become challenging. In view of this an optimization algorithm would be required where

Table 8a

Energy generated by different units in each of the nine networks. The total energy content of the biomass used for energy generation is 33.28 MW.

	Fuel cells (MW)	Gas turbines (MW)	Heat recovery (MW)	Parasitic losses (MW)	Total energy (MW)	Efficiency
Network 1	0	12.49	1.49	1.17	12.81	38.49%
Network 2	4.13	8.86	1.49	1.47	13.01	39.09%
Network 3	8.35	4.28	1.49	1.74	12.38	37.20%
Network 4	10.01	1.56	1.48	2.25	10.79	32.42%
Network 5	11.56	0	1.49	1.86	10.78	32.39%
Network 6	0	12.54	1.54	1.51	12.57	37.76%
Network 7	3.91	7.70	1.49	1.39	11.71	35.18%
Network 8	8.82	2.99	1.43	2.08	11.17	33.56%
Network 9	11.21	0	1.44	1.96	10.69	32.13%

the simulation model can be used in the optimization algorithm (simulation-optimization – Sim-Opt) to obtain the best values for the variables that are being optimized. The study by Ahmadi et al. [56] is amongst the few such studies where an MOO was used to optimize a combined cycle. In contrast we use an MOO for an IGFC system. Further, we propose a superstructure that considers fuel cell bottoming cycle, fuel cell topping cycle and combinations of the two and solve the superstructure in a Sim-Opt environment that allows us to obtain multiple optimal networks in a single optimization run. This allows elimination of sub-optimal networks by the algorithm and without relying on subjective human judgement. For example, we have observed that it is better to run the combustion/gasification processes at extreme partial combustion for increased efficiency rather than to use water–gas shift reaction for increasing hydrogen production. We know that the water–gas shift reaction is an endothermic reaction [24]; however, it has been widely proposed [54] as a means to increase the hydrogen content of the Syngas that is produced from biomass/natural gas. However, our optimization algorithm eliminated this while performing superstructure optimization.

In their study, Bang-Møller et al. [47] considered a reference plant that produces about 18% of the total energy from gas turbine, while the gas turbine in the optimized system produces about 22% of the total energy. This observation is qualitatively similar to our observations that the capacity (or contribution) of the gas turbines in IGFC can be increased to achieve higher efficiency. Further, the turbine inlet temperature (TIT) of their system was up to 950 °C (1223 K) while we have observed a TIT of up to 1200 °C (1473 K) in our study. Other researchers [63] studied two systems, the first

Table 8b

Energy generated by different units when natural gas is used as fuel. The total energy content of the natural gas used for energy generation is 67.68 MW.

	Fuel cells (MW)	Gas turbines (MW)	Heat recovery (MW)	Parasitic losses (MW)	Total energy (MW)	Efficiency
Network A	41.25	0	2.2	5.08	38.37	56.85%
Network B	26.72	6.7	2.4	4.33	31.49	46.66%
Network C	13.34	9.35	1.99	4.37	20.31	30.09%

being an atmospheric system that has an SOFC with HRGS and second a high-pressure system that has a gas turbine in addition to SOFC and HRGS. They have demonstrated that the high-pressure system (with gas turbine) has a higher electrical efficiency at 71.9% compared to only 64.6% for the atmospheric pressure system (no gas turbine). It should be mentioned here that the TIT from this study is 1019 °C (1292 K) which is lower than what we observed. Further, the results of this study are in qualitative agreement with our observations that a gas turbine would be necessary when biomass is used as fuel.

In a recent study by Rokni [67], a system comprising an SOFC and Stirling engine is analyzed and the TIT in their study (1268 °C or 1541 K) is closer to what we have observed. This may be because we have set constraints in our optimization problem to limit the TIT to 1473 K to avoid material fatigue. Rokni has mentioned that Stirling engines hold great promise for use in IGFCs and this can be attributed to the higher TIT compared to other systems. Although we have analyzed gas turbines and not Stirling engine, the observation of a higher TIT for better design of an IGFC is similar in both Rokni's and our study. In addition, Rokni has also studied thermo-economic analysis along with thermodynamic analysis of IGFC with Stirling engine [68]. However, such a study is beyond the scope of this work because of the complexities that CapEx would bring to the superstructure optimization.

Further, the size of the gas turbine in these studies is usually smaller than the fuel cells because the gas turbine is in the bottoming cycle. The fuel utilization in the fuel cells is varied manually and the influence of the same on the efficiency of the system is analyzed. On the contrary, we have considered fuel cell bottoming networks also in our superstructure and this allows us to analyze systems with larger gas turbines. Further, having all the variables in the MOO allows us to simultaneously size the fuel cells and gas turbines and also optimise the operating conditions.

In our study, we have observed that the contribution of the gas turbine can be over and above 50% of the total energy generated (Networks 6 & 7) when biomass is used as fuel. In view of this, it would be worthwhile to perform detailed analysis on such a plant to confirm the validity of the observed results. However, this would constitute a study on its own and is beyond the scope of this work. This can be attributed to two factors. First, gas turbines recover energy by expansion and hence, the temperature of the spent gases is lower than that from the fuel cells, thereby allowing greater energy production. Second, the efficiency of the HRGS system is only 65% and there is more energy destruction in heat recovery from spent gases coming out of the fuel cells stream due to its higher temperature than that coming out of the gas turbines.

From the results of this study, the immediate question that arises is the practicality of the various biomass based IGFCs that are being planned around the world. Hence, it must be emphasized that the results of this study highlight the thermodynamic upper limit and that the actual plant which is sub-optimal may still be planned. The efficiency of the power plant also depends on the ancillary equipments that are present. If natural gas based IGFC is planned, then no comparison with detailed design of IGCC may be required. However, if a biomass based IGFC is being planned, a comparison with the detailed design of the IGCC is required to see the real benefits of using fuel cells.

5. Conclusions

In this work, MOO was used to obtain multiple optimal designs for the generation of energy from an integrated gasification fuel cell/gas turbine cycle. It was observed that fuel cell only design, gas turbine only design and fuel cell topping design can all generate about the same amount of energy when biomass is used as fuel.

However, when natural gas is used as fuel and the combustion/gasification units are maintained at Gibbs equilibrium, fuel cell only network generates considerable higher energy than other networks. Hence, we conclude that natural gas is the preferred fuel over biomass when fuel cells are used and that it is of utmost importance to maintain the process at Gibbs equilibrium for maximum energy production. If maintaining the combustion and gasification units at Gibbs equilibrium is operationally difficult, then gas turbines must be preferred over fuel cells. In view of the large number of networks represented on the Pareto front, the current analysis is limited to manually selecting a few networks and presenting the best result. However, it would be worthwhile to develop algorithms that can sieve different networks and check if there are other networks that are of importance.

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References

- [1] International Energy Agency. Energy technology perspectives 2008 – scenarios & strategies to 2050. IEA Publications Bookshop; 2008 [last accessed: 28 May 2013]. <http://www.iea.org/media/etp/ETP2008.pdf>.
- [2] Narahariseti PK, Karimi IA, Abhay Anand, Lee DY. A linear diversity constraint – application to scheduling in microgrids. *Energy* 2011;36(7):4235–43. Lee.
- [3] ExxonMobil energy outlook 2013. Outlook for Energy: a view to 2040.
- [4] Li M, Rao DA, Brouwer J, Samuelsen GS. Design of highly efficient coal based integrated gasification fuel cell power plants. *J Power Sources* 2010;195: 5707–18.
- [5] Omosun AO, Bauen A, Brandon NP, Adjiman CS, Hart D. Modelling system efficiencies and costs of two biomass-fuelled SOFC systems. *J Power Syst* 2004;131:96–106.
- [6] Lee JC, Lee HH, Joo YJ, Lee CH, Oh M. Process simulation and thermodynamics analysis of an IGCC (integrated gasification combined cycle) plant with an entrained gasifier. *Energy* 2014;64:58–68.
- [7] Ergun S. Kinetics of the reactions of carbon dioxide and steam with coke. U.S. Bureau of Mines Bulletins, U.S. Bureau of Mines; 1962.
- [8] Tu CM, Davis H, Hottel HC. Combustion rate of carbon. *Int Commun Heat Mass Transf* 1984;11:15–23.
- [9] Brunello S, Fluor I, Maissa P, Bruyet B. Kinetic study of char combustion in a fluidized bed. *Fuel* 1996;75(5):536–44.
- [10] Atkinson B, Merrick D. Mathematical models for the thermal decomposition of coal 4. Heat transfer and temperature profiles in a coke-oven. *Fuel* 1983;62: 553–61.
- [11] Merrick D. Mathematical models for the thermal decomposition of coal 1. The evolution of volatile matter. *Fuel* 1983;62:534–9.
- [12] Merrick D. Mathematical models for the thermal decomposition of coal 2. Specific heats and heats of reaction. *Fuel* 1983;62:540–6.
- [13] Merrick D. Mathematical models for the thermal decomposition of coal 3. Density, porosity and contraction behaviour. *Fuel* 1983;62:547–52.
- [14] Voller VR, Cross M, Merrick D. Mathematical models for the thermal decomposition of coal 5. Distribution of gas flow in a coke oven charge. *Fuel* 1983;62:562–70.
- [15] Henrich E, Burkley S, Meza-Renken ZI, Rumpel S. Combustion and gasification kinetics of pyrolysis chars from waste and biomass. *J Anal Appl Pyrolysis* 1999;49:221–41.
- [16] Mandl C, Obernberger I, Biedermann F. Modelling of an updraft fixed bed gasifier operated with softwood pellets. *Fuel* 2010;89:3795–806.
- [17] Gomez-Barea A, Leckner B. Modeling of biomass gasification in fluidized bed. *Prog Energy Combust Sci* 2010;36:444–509.
- [18] Vitasari CR, Jurascik M, Ptasiński KJ. Exergy analysis of biomass-to-synthetic natural gas (SNG) process via indirect gasification of various biomass feedstock. *Energy* 2011;36:3825–37.
- [19] Perez-Fortes M, Bojarski AD, Velo E, Nougues JM, Puigjaner L. Conceptual model and evaluation of generated power and emissions in an IGCC plant. *Energy* 2009;34:1721–32.
- [20] Schuster G, Loffer G, Weigl K, Hofbauer H. Biomass steam gasification – an extensive parametric modeling study. *Bioresour Technol* 2001;77:71–9.
- [21] Kaushal P, Proll T, Hofbauer H. Model for biomass char combustion in the riser of a dual fluidized bed gasification unit: part 1 – model development and sensitivity analysis. *Fuel Process Technol* 2008;89:651–9.
- [22] Kaushal P, Abedi J, Mahinpey N. A comprehensive mathematical model for biomass gasification in a bubbling fluidized bed reactor. *Fuel* 2010;89: 3650–61.

- [23] Campoy M, Gomez-Barea A, Vidal FB, Ollero P. Air–steam gasification of biomass in a fluidized bed: process optimization by enriched air. *Fuel Process Technol* 2009;90(5):677–85.
- [24] Choi Y, Stenger HG. Water gas shift reaction kinetics and reactor modeling for fuel cell grade hydrogen. *J Power Sources* 2003;124:432–9.
- [25] Klose W, Wolki M. On the intrinsic reaction rate of biomass char gasification with carbon dioxide and steam. *Fuel* 2005;84:885–92.
- [26] Everson RC, Neomagus HWJP, Kasaini H, Njapha D. Reaction kinetics of pulverized coal-chars derived from inertinite-rich coal discards: characterization and combustion. *Fuel* 2006;85:1067–75.
- [27] Trommer D, Steinfeld A. Kinetic modeling for the combined pyrolysis and steam gasification of petroleum coke and experimental determination of the rate constants by dynamic thermogravimetry in the 500–1520 K range. *Energy Fuels* 2006;20(3):1250–8.
- [28] Lee DH, Yang H, Yan R, Liang DT. Prediction of gaseous products from biomass pyrolysis through combined kinetic and thermodynamic simulations. *Fuel* 2007;86:410–7.
- [29] Piatkowski N, Steinfeld A. Reaction kinetics of the combined pyrolysis and steam-gasification of carbonaceous waste materials. *Fuel* 2010;89:1133–40.
- [30] Yang H, Yan R, Chen H, Zheng C, Lee DH, Liang DT. In-depth investigation of biomass pyrolysis based on three major components: hemicellulose, cellulose and lignin. *Energy Fuels* 2006;20(1):388–93.
- [31] Guo B, Li D, Cheng C, Lu Z, Shen Y. Simulation of biomass gasification with a hybrid neural network model. *Bioresour Technol* 2001;76:77–83.
- [32] Yanbing L, Baosheng J, Rui X. Carbon dioxide reforming of methane with a free energy minimization approach. *Korean J Chem Eng* 2007;24(4):688–92.
- [33] Baggio P, Baratieri M, Fiori L, Grigiante M, Avi D, Tosi P. Experimental and modeling analysis of a batch gasification/pyrolysis reactor. *Energy Convers Manag* 2009;50:1426–35.
- [34] Li M, Brouwer J, Rao AD, Samuelsen GS. Application of a detailed dimensional solid oxide fuel cell model in integrated gasification fuel cell design and analysis. *J Power Sources* 2011;196:5903–12.
- [35] Roberts RA, Brouwer J, Jabbari F, Junker T, Ghezal-Ayagh H. Control design of an atmospheric solid oxide fuel Cell/Gas turbine hybrid System: variable versus fixed speed Gas turbine operation. *J Power Sources* 2006;161:484–91.
- [36] Kaneko T, Brouwer J, Samuelsen GS. Power and temperature control of fluctuating biomass gas fueled solid oxide fuel cell and micro gas turbine hybrid system. *J Power Sources* 2006;160:316–25.
- [37] Mueller F, Jabbari F, Gaynor R, Brouwer J. Novel solid oxide fuel cell system controller for rapid load following. *J Power Sources* 2007;172:308–23.
- [38] Mueller F, Gaynor R, Auld AE, Brouwer J, Jabbari F, Samuelsen GS. Synergistic integration of gas turbine and solid oxide fuel cell for improved transient capability. *J Power Sources* 2008;176:229–39.
- [39] Ferrair M, Traverso A, Magistri L, Massardo AF. Influence of the anodic recirculation transient behaviour of the SOFC hybrid system performance. *J Power Syst* 2005;149:22–32.
- [40] Magistri L, Traverso A, Cerutti F, Bozzolo M, Costamagna P. Modelling of pressurized hybrid systems based on integrated planar solid oxide fuel cell (IP-SOFC) technology. *Fuel Cells* 2005;5:80–96.
- [41] Chan SH, Ho HK, Tian Y. Multi-level modeling of SOFC-gas turbine hybrid system. *Int J Hydrog Energy* 2003;28:889–900.
- [42] Chan SH, Ho HK, Tian Y. Modelling for part-load operation of solid oxide fuel cell-gas turbine hybrid power plant. *J Power Syst* 2003;114:213–27.
- [43] Chan SH, Ho HK, Tian Y. Modelling of simple hybrid solid oxide fuel cells and gas turbine power plant. *J Power Syst* 2002;109:111–20.
- [44] Costamagna P, Magistri L, Massardo AF. Design and part-load performance of a hybrid system based on a solid oxide fuel cell reactor and a micro turbine. *J Power Sources* 2001;96:352–68.
- [45] Murshed AKMM, Huang B, Nandakumar K. Control relevant modeling of planar solid oxide fuel cell system. *J Power Sources* 2007;163:830–45.
- [46] Murshed AKMM, Huang B, Nandakumar K. Estimation and control of solid oxide fuel cell system. *Comput Chem Eng* 2010;34:96–111.
- [47] Bang-Møller C, Rokni M, Elmegaard B. Exergy analysis and optimization of a biomass gasification, solid oxide fuel cell and micro gas turbine hybrid system. *Energy* 2011;36(8):4740–52.
- [48] Bang-Møller C, Rokni M, Elmegaard B, Ahrenfeldt J, Henriksen UB. Decentralized combined heat and power production by two-stage biomass gasification and solid oxide fuel cells. *Energy* 2013;58:527–37.
- [49] Kalantar M, Mousavi GSM. Dynamic behavior of a stand alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage. *Appl Energy* 2010;87:3051–64.
- [50] Chacartegui R, Sanchez D, Munoz A, Sanchez T. Real time simulation of medium size gas turbine. *Energy Convers Manage* 2011;52:713–24.
- [51] Panopoulos KD, Fryda LE, Karl J, Poulou S, Kakaras E. High temperature solid oxide fuel cell integrated with novel allothermal biomass gasification Part I: modelling and feasibility study. *J Power Sources* 2006;159:570–85.
- [52] Panopoulos KD, Fryda LE, Karl J, Poulou S, Kakaras E. High temperature solid oxide fuel cell integrated with novel allothermal biomass gasification Part II: exergy analysis. *J Power Sources* 2006;159:586–94.
- [53] Fryda L, Panopoulos KD, Karl J, Kakaras E. Exergetic analysis of solid oxide fuel cell and biomass gasification integration with heat pipes. *Energy* 2008;33:292–9.
- [54] Doherty W, Reynolds A, Kennedy D. Computer simulation of a biomass gasification-solid oxide fuel cell power system using Aspen Plus. *Energy* 2010;35(12):4545–55.
- [55] Heidebrecht P, Hartono B, Hertel C, Sundmacher K. Biomass-based fuel cell power plants: evaluation of novel reactors and process designs. *Ind. Eng. Chem. Res.* 2010;49(21):10,859–10,875.
- [56] Ahmadi P, Dincer I, Rosen MA. Exergy, exergoeconomic and environmental analyses and evolutionary algorithm based multi-objective optimisation of combined cycle power plants. *Energy* 2011;5886–98.
- [57] Ahmadi P, Dincer I, Rosen MA. Thermoeconomic multi-objective optimization of a novel biomass-based integrated energy system. *Energy* 2014;68:958–70.
- [58] Sadhukan J, Zhao Y, Shah N, Brandon N. Performance analysis of integrated biomass gasification fuel cell (BGFC) and biomass gasification combined cycle (BGCC) systems. *Chem Eng Sci* 2010;1942–54.
- [59] Kaikko J, Backman J, Koskelainen L, Larjola KJ. Technical and economic performance comparison between recuperated and non-recuperated variable-speed microturbines in combined heat and power generation. *Appl Therm Eng* 2007;27:2173–80.
- [60] Liszka M, Malik M, Budnik M, Ziebig A. Comparison of IGCC (integrated gasification combined cycle) and CFB (circulating fluidised bed) cogeneration plants equipped with CO₂ removal. *Energy* 2013;58:86–96.
- [61] Naraharisetti PK, Karimi IA, Srinivasan R. Supply chain redesign—multimodal optimization using a hybrid evolutionary algorithm. *Ind Eng Chem Res* 2009;48:11,094–11,107.
- [62] Larmine J, Dicks A. In: *Fuel cell systems explained*. 2nd ed. England: Wiley; 2003.
- [63] Gandiglio M, Lanzini A, Leone P, Santarelli M, Borchellini R. Thermoeconomic analysis of large solid oxide fuel cell plants: atmospheric vs. pressurized performance. *Energy* 2013;55:142–55.
- [64] Deb K. *Multi-objective optimisation using evolutionary algorithms*. Chichester, New York: John Wiley & Sons; 2001.
- [65] Zheng H, Kaliyan N, Vance Morey R. Aspen Plus simulation of biomass integrated gasification combined cycle systems at corn ethanol plants. *Biomass Bioenergy* 2013;197–210.
- [66] Skorek-Osikowska A, Bartela L, Kotowicz J, Sobolewski A, Illuk T, Remiorz L. The influence of the size of the CHP (combined heat and power) system integrated with a biomass fueled gas generator and piston engine on the thermodynamic and economic effectiveness of electricity and heat generation. *Energy* 2014;67:328–40.
- [67] Rokni M. Biomass gasification integrated with a solid oxide fuel cell and Stirling engine. *Energy* 2014. <http://dx.doi.org/10.1016/j.energy.2014.01.078>.
- [68] Rokni M. Thermodynamic and thermoeconomic analysis of a system with biomass gasification, solid oxide fuel cell (SOFC) and Stirling engine. *Energy* 2014. <http://dx.doi.org/10.1016/j.energy.2014.01.106>.